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Published in:
Organic Electronics

DOI:
10.1016/j.orgel.2008.03.009

Organic Electronics 9 (2008) 617–624

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Device operation of organic tandem solar cells

A. Hadipour, B. de Boer, P.W.M. Blom *

Molecular Electronics, Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, NL-9747 AG Groningen, The Netherlands

ARTICLE INFO

Article history:
Received 24 October 2007
Received in revised form 14 March 2008
Accepted 21 March 2008
Available online 4 April 2008

Keywords:
Organic solar cells
Tandem solar cells
Device physics

ABSTRACT

A generalized methodology is developed to obtain the current–voltage characteristic of polymer tandem solar cells by knowing the electrical performance of both sub cells. We demonstrate that the electrical characteristics of polymer tandem solar cells are correctly predicted for both the series and parallel connection of the sub cells. The agreement with experiments allows us to investigate the effect of a reduced open-circuit voltage, short-circuit current or fill factor in one of the sub cells on the performance of the tandem cell. A low fill factor in one of the sub cells leads to a stronger reduction of the efficiency in a series configuration as compared to the parallel tandem device.

1. Introduction

In order to make relatively cheap solar cells for large-area applications, organic materials are promising candidates. However, the narrow absorption properties combined with low charge carrier mobilities limit the performance of the organic solar cells [1,2]. One way to improve the absorption of organic solar cells is by using tandem (or multi-junction) structures [3–10]. Because of the different band gap of the active layer each sub cell then absorbs light in a different part of the solar spectrum. In order to further optimize the performance of organic tandem solar cells, it is important to understand their operation. The ability to predict the performance of tandem cells, either in series or parallel configuration, from the performance of the individual sub cells will strongly reduce the experimental work needed to reach the optimum device structure. In order to understand the electrical properties of a tandem organic solar cell, we consider here a tandem cell that is based on two sub cells with totally different electrical properties. In this general case, the bottom cell generates a higher current, but lower voltage as compared to the top cell. The presented methodology demonstrates how the electrical characteristics of tandem cells that are either connected in series or parallel, can be predicted from the characteristics of the sub cells.

In order to compare the calculated results with experiment, a 4-electrode tandem cell is used in which the bottom and top cells are separated by an optical spacer [9] (inset Fig. 5). The use of such a device structure has two advantages; first, because of the presence of 4 electrodes the *J–V* characteristics of the individual bottom and top cell as well as the tandem cell can be measured in one single device. Second, since the sub cells are electrically separated, both the series and parallel configuration can be measured within the same device. In this way the test conditions are exactly the same for all cells. In Fig. 1 the current–voltage characteristics are shown for a tandem cell based on a 250 nm blend of regioregular poly(3-hexylthiophene) (rr-P3HT) and the fullerene derivative [6,6]-phenyl-C_{61}-butyric acid methyl ester (PCBM) for the bottom cell and a 80 nm blend of poly(2-methoxy-5-(3′,7′-dimethyloctyloxy)-*p*-phenylene vinylene) (MDMO-PPV) and PCBM for the top cell. An optical spacer with a thickness of 190 nm was used to separate the sub cells. The question now is how the *J–V* characteristic of a tandem cell based on those two sub cells will look like, when they are electrically connected in series or in parallel. As a first step we consider the series configuration and subsequently the parallel tandem cell is addressed. Then the obtained

* Corresponding author. Tel.: +31 50 3634376; fax: +31 50 3638751.
E-mail address: p.w.m.blom@rug.nl (P.W.M. Blom).

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doi:10.1016/j.orgel.2008.03.009

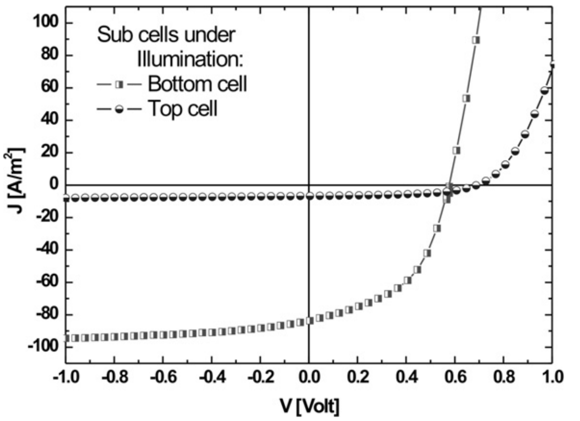

Fig. 1. The current–voltage characteristic of two sub cells under illumination. The top cell delivers higher open-circuit voltages, while its photocurrent is much lower than the bottom cell.

tandem cell J–V characteristics are compared to experimental data.

2. Current density–voltage characteristics for series and parallel configurations

2.1. Series configuration

When the two sub cells are connected in series, the total generated photocurrent will be constant throughout the device (conservation of charge) in steady-state. Furthermore, the voltages generated by the sub cells will add up. As a result for each point of the J–V characteristic of the tandem device the following relations are valid,

$$J_{\text{Tandem}} = J_{\text{Bottom}} = J_{\text{Top}} \tag{1}$$

$$V_{\text{Tandem}} = V_{\text{Bottom}} + V_{\text{Top}} \tag{2}$$

Graphically, Eq. (1) means that we can draw an arbitrary horizontal line through Fig. 1, indicating a chosen constant current density that flows through the cells. This horizontal line crosses the J–V curves under illumination of the individual bottom and the top cell at a specific voltage for each sub cell. Those cross-points are the values of the voltages with which the sub cells are effectively biased in order to generate the chosen constant current density. Eq. (2) then shows that we have to add those two voltage values in order to determine the bias voltage of the tandem cell in series at that constant current density. To do so, we replot Fig. 1 between zero and −10 A/m^2 in order to enlarge the vertical axis and choose three arbitrary current densities as shown in Fig. 2. The horizontal line 1 is the open-circuit condition for both sub cells in which the current densities in both of them are zero (cross-points A and B). Line 2 shows the short-circuit condition of the top cell (cross-point C), whereas the bottom sub cell is biased by a positive voltage (cross-point D). Line 3 is the condition in which the bottom cell is biased by a positive voltage (cross-point F), whereas the top is biased by a negative voltage (cross-point E).

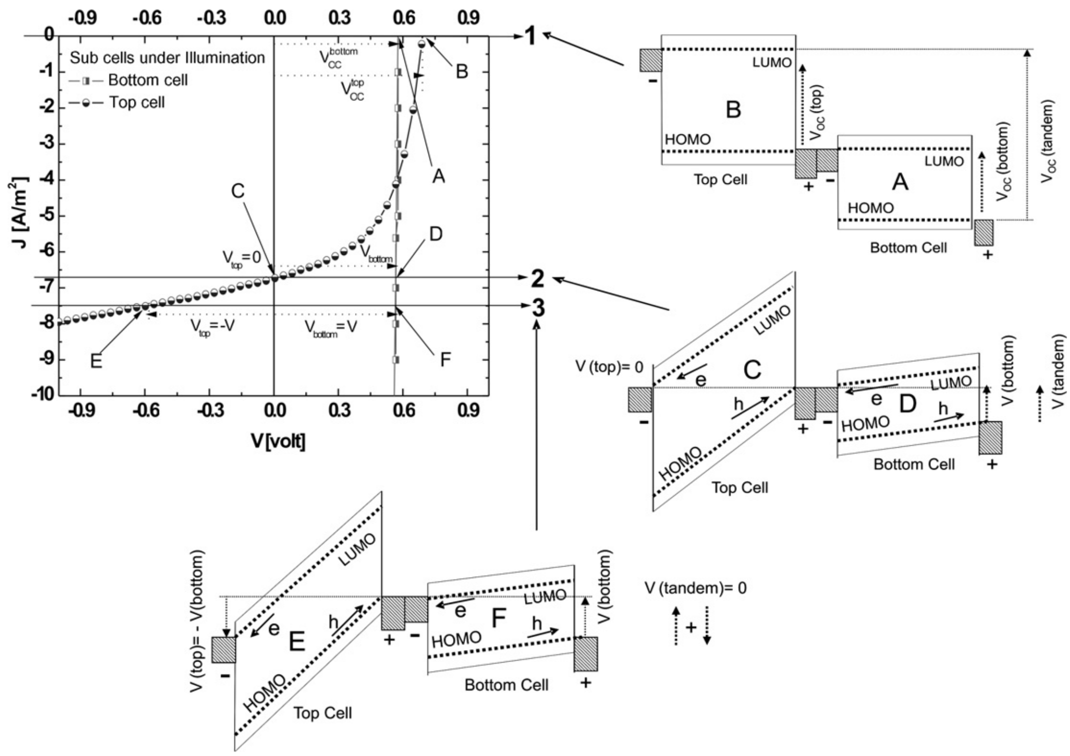

Fig. 2. A close-up of the vertical axis of Fig. 1 between 0 and −10 A/m^2. The horizontal lines 1–3 cross the curves of the bottom (A, D and F) and top cells (B, C and E), indicating a constant current density. For each line the energy-band diagrams are given.

Following Eqs. (1) and (2) we can say that,

At line 1:

$$J_{\mathrm{Tandem}} = J_{\mathrm{Bottom}} = J_{\mathrm{Top}} = J_1 = 0\ [\mathrm{A/m^2}] \tag{3}$$

$$V_{\mathrm{OC}}^{\mathrm{Tandem}} = V_{\mathrm{OC}}^{\mathrm{Bottom}} + v_{\mathrm{OC}}^{\mathrm{Top}} = V_{\mathrm{A}} + V_{\mathrm{B}} = (0.57) + (0.7) = 1.27\ [\mathrm{V}] \tag{4}$$

At line 2:

$$J_{\mathrm{Tandem}} = J_{\mathrm{Bottom}} = J_{\mathrm{SC}}^{\mathrm{Top}} = J_2 = -6.68\ [\mathrm{A/m^2}] \tag{5}$$

$$V_{\mathrm{Tandem}} = V_{\mathrm{Bottom}} + V_{\mathrm{Top}} = V_{\mathrm{C}} + V_{\mathrm{D}} = (0) + (0.56) = 0.56\ [\mathrm{V}] \tag{6}$$

At line 3:

$$J_{\mathrm{SC}}^{\mathrm{Tandem}} = J_{\mathrm{Bottom}} = J_{\mathrm{Top}} = J_3 = 7.46\ [\mathrm{A/m^2}] \tag{7}$$

and because for this current density of line 3 the distance from E and F to the y-axis are equal,

$$V_{\mathrm{Tandem}} = V_{\mathrm{Bottom}} + V_{\mathrm{Top}} = V_{\mathrm{E}} + V_{\mathrm{F}} = (-0.55) + (0.55) = 0\ [\mathrm{V}] \tag{8}$$

In this way the open-circuit voltage (Eq. (4)), short-circuit current (Eq. (7)) and an additional arbitrary point (at short-circuit condition of the top cell) of the series tandem cell are predicted. In Fig. 2 also the energy-band diagrams are schematically depicted for these three cases. We now discuss the biasing conditions of this series tandem cell in more detail. In a series configuration the cathode of the bottom cell is electrically connected to the anode of the top cell. In the tandem cell studied here the bottom cell generates much more photocurrent than the top cell (Fig. 1) under, for example, short-circuit condition. This implies that there are not enough holes arriving from the top cell to recombine with the large amount of electrons arriving from the bottom cell. As a result, in steady-state, the excess of electrons will negatively charge the connected electrodes of the sub cells. This charging reduces the effective voltage across the bottom cell, and thus also the extracted current from the bottom cell. On the other hand, the additional electrons in the middle electrode provide a stronger voltage-drop across the top cell (the top cell is more reversed biased) and, therefore, a higher current flows through the top cell. Steady-state is reached when the lowered current in the bottom cell is equal to the enhanced current of the top cell. At the open-circuit voltage (line 1) both the sub cells are biased in such a way that the effective electric field across them is close to zero (the bias neutralizes the built-in electric field). Current matching is then achieved since both cells do not generate any current: they only act as two voltage sources of which the generated voltages add up. Line 2 shows the situation where the effective bias across the top cell is zero (C), meaning that the field across the top cell is now equal to its built-in electric field. Due to the negative charging of the middle electrode, the effective voltage across the bottom cell is strongly reduced (D) in order to balance the current with the top cell. For line 3, the electric field across the top cell is even further enhanced by the increasing amount of charge on the middle electrode, such that the top cell is now reverse (negative) biased. In this case, the electric field across the top cell is larger than its built-in electric field (E). Finally, line 3 is chosen in such a way that the negative bias across the top cell (E) is equal to the positive bias of the bottom cell (F). As a result the total voltage across the tandem equals zero, such that line 3 represents the short-circuit current of the tandem cell. By choosing sufficient horizontal lines (current levels) and extracting the voltages as mentioned above, the whole illuminated J–V curve of the series tandem cell can be constructed.

2.2. Parallel configuration

When the two sub cells are electrically connected in parallel, in steady-state, for each point of the J–V characteristics of the tandem device the following relations are valid,

$$V_{\mathrm{Tandem}} = V_{\mathrm{Bottom}} = V_{\mathrm{Top}} \tag{9}$$

$$J_{\mathrm{Tandem}} = J_{\mathrm{Bottom}} + J_{\mathrm{Top}} \tag{10}$$

Graphically, Eq. (9) means that we can now draw an arbitrary vertical line through Fig. 1, which indicates the chosen operating voltage for the sub cells. This vertical line crosses the J–V characteristics under illumination of the bottom and the top cell at a specific current for each cell. Those cross-points are the values of the current density generated by the sub cells at the chosen operating voltage. These two values of the current densities of the bottom and top cell then have to be added (Eq. (10)) to calculate the current of the parallel tandem cell for the chosen operating voltage. We now enlarge the horizontal axis of Fig. 1 and again draw three vertical lines, as shown in Fig. 3. The vertical line 1 is the open-circuit condition for the top cell and positive current density for the bottom cell (cross-points K and L). Line 2 shows the condition in which the sub cells have opposite current densities. At line 2, the bottom cell generates positive current due to dark injection (cross-point M), whereas the top cell generates a negative photocurrent (cross-point N). Line 3 is the short-circuit condition for all cells in which both the bottom cell (cross-point O) and the top cell (cross-point P) generate negative photocurrents.

From Eqs. (9) and (10) we obtain that:

At line 1:

$$V_{\mathrm{Tandem}} = V_{\mathrm{Bottom}} = V_{\mathrm{OC}}^{\mathrm{Top}} = V_1 = 0.69\ [\mathrm{V}] \tag{11}$$

$$J_{\mathrm{Tandem}} = J_{\mathrm{Bottom}} + J_{\mathrm{Top}} = J_{\mathrm{K}} + J_{\mathrm{L}} = (87.5) + (0) = 87.5\ [\mathrm{A/m^2}] \tag{12}$$

At line 2:

$$V_{\mathrm{OC}}^{\mathrm{Tandem}} = V_{\mathrm{Bottom}} = V_{\mathrm{Top}} = V_2 = 0.58\ [\mathrm{V}] \tag{13}$$

since M and N have equal distance to the x-axis,

$$J_{\mathrm{Tandem}} = J_{\mathrm{Bottom}} + J_{\mathrm{Top}} = J_{\mathrm{M}} + J_{\mathrm{N}} = (4.0) + (-4.0) = 0\ [\mathrm{A/m^2}] \tag{14}$$

At line 3:

$$V_{\mathrm{Tandem}} = V_{\mathrm{Bottom}} = V_{\mathrm{Top}} = V_3 = 0\ [\mathrm{V}] \tag{15}$$

$$J_{\mathrm{SC}}^{\mathrm{Tandem}} = J_{\mathrm{SC}}^{\mathrm{Bottom}} + J_{\mathrm{SC}}^{\mathrm{Top}} = J_{\mathrm{O}} + J_{\mathrm{P}} = (-83.65) + (-7.1) = -90.75\ [\mathrm{A/m^2}] \tag{16}$$

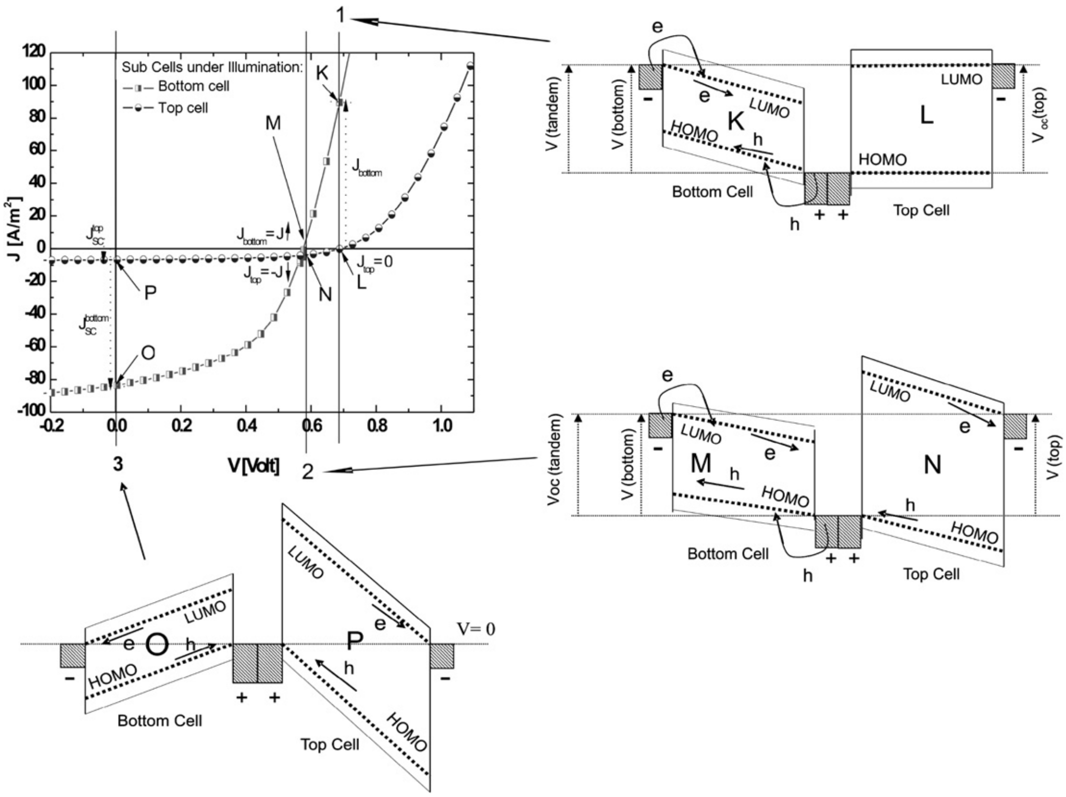

Fig. 3. Close-up of the horizontal axis of Fig. 1 between −0.2 and 1 V. By extracting the cross-points of the vertical lines with the *J–V* curve of the bottom cell (K, M and O), and the top cell (L, N and P) from the graph, the current density of the parallel tandem device can be constructed for a range of chosen voltages. The energy-band diagrams in the different operation points are also given.

With this method, the short-circuit current, open-circuit voltage and an additional point of the *J–V* characteristic are determined for a parallel tandem cell based on the sub cells mentioned before. By drawing sufficient vertical lines through the *J–V* curves of the sub cells and extracting the operation points the complete *J–V* characteristic of the parallel tandem device can be constructed. Also shown in Fig. 3 are the corresponding energy-band diagrams for the three lines. In the parallel configuration the two outer electrodes are connected and show up on an equal level in these diagrams. For line 1 the top cell is biased such that the electric field across the cell is close to zero (L). However, because of the lower built-in field in the bottom cell, the electric field in the bottom cell changes sign (K) under this bias. As a result the dark injection in the bottom cell is switched on and electrons now flow to the PEDOT:PSS in stead of to the LiF/Al electrode, leading to a positive current. For the voltage corresponding to line 2 the bottom cell is still dominated by (positive) dark current, but its current is now of equal magnitude as the (negative) photocurrent generated by the top cell. Therefore, this voltage represents the open-circuit voltage of the tandem cell and is located in between the V_{OC} is of the individual cells. Finally, line 3 shows the situation when no bias is applied across the parallel tandem. In that case both sub cells are effectively biased by their built-in electrical fields. Using the procedures described in this section, the current–voltage curve of any parallel – and series connected tandem solar cell can be derived from the electrical performance of the individual sub cells. It should be noted that this method can also be used for the prediction of the *J–V* curves of multi-junction organic solar cells with three or more active layers [1]. The constructed *J–V* curve of the series and parallel tandem cell is shown in Fig. 4, together with the characteristics of the individual sub cells.

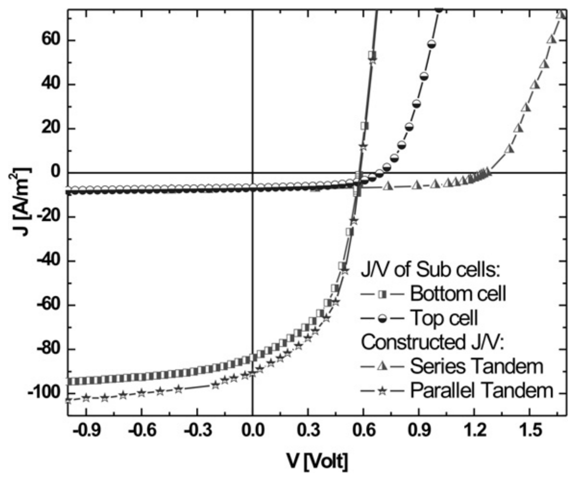

Fig. 4. Current–voltage characteristic of the two sub cells, and the constructed series and parallel tandem solar cell.

3. Comparison with experiment

To compare the calculated *J*–*V* characteristics of the tandem cells with experimental data we can use the measurements on the tandem device as described in Ref. [9] (inset Fig. 5). As stated above the tandem cell we consider is based on a 250 nm P3HT:PCBM blend for the bottom cell and a 80 nm MDMO-PPV:PCBM blend for the top cell, separated by an optical spacer with a thickness of 190 nm. For this thickness the optical spacer maximizes the transmitted light for the wavelengths that correspond to the absorption spectrum of the MDMO-PPV [9]. The experimental *J*–*V* characteristics of the individual bottom and top cell of this structure were already shown in Fig. 1. The complete structure of this tandem test device is given in the inset of Fig. 5. The two sub cells can be connected electrically in series or in parallel using external wiring. In Fig. 5, the results of the measured *J*–*V* curves are compared to the constructed *J*–*V* curves as shown in Fig. 4. The experimental *J*–*V* characteristics are in excellent agreement with the predicted values. To make a more quantitative comparison, we determined for the calculated and experimental *J*–*V* curves of Fig. 5 (series and parallel connection) the exact values for V_{OC} and J_{SC}, the voltage V_{max} and the current density J_{max} at the maximum power point, and the corresponding fill factor (FF) and efficiency η. The results are summarized in Table 1.

Clearly, all relevant solar cell parameters for the series and parallel connected tandem cells can be accurately predicted from the electrical characteristics of the individual sub cells (Table 1). Verification of the predicted characteristics with experimental data now allows us to systematically investigate the effect of a series and parallel connection of subcells with different open-circuit voltages, short-circuit currents and fill factors.

4. The efficiency of tandem solar cells with non-identical subcells

Another important question is how the performance of a tandem cell is affected, when one of the sub cells has a poor performance. Such a low performance might be the result of a low V_{OC}, J_{SC} or poor FF. To investigate the role of either a low V_{OC}, J_{SC} or FF in one of the subcells we construct a series of *J*–*V* characteristics in which one of these parameters is systematically varied. The other two parameters are kept constant for clarity. As an example in Fig. 6 *J*–*V* characteristics are shown in which the V_{OC} is systematically varied. These artificial *J*–*V* curves are constructed in such a way that all cells have the same FF and J_{SC}, but a large variation in V_{OC} (from 0.59 V to 0.29 V). With these 6 cells as input we can now construct on paper a series

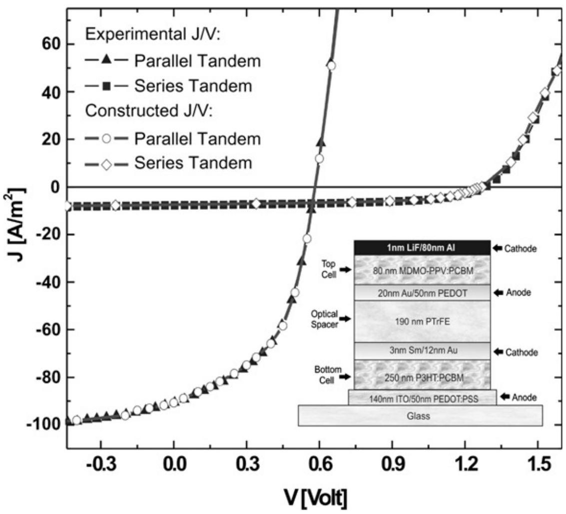

Fig. 5. The comparison between experiment and generated current–voltage characteristics. The constructed curves are in very good agreement with the experimental obtained data in both series and parallel configurations. Inset: structure of the tandem test device. The electrodes of the device can be electrically connected in parallel or in series by adjusting the external wires.

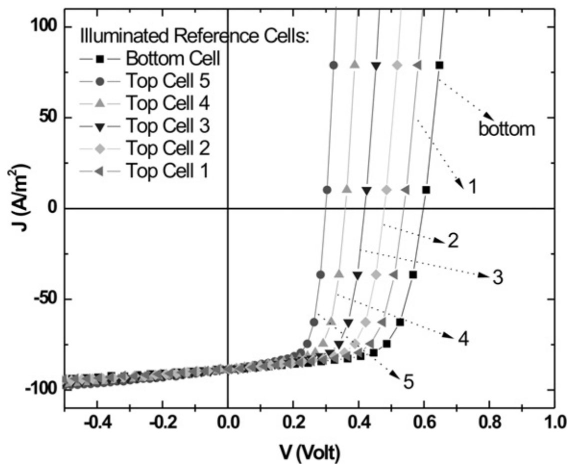

Fig. 6. Current–voltage characteristic of 6 artificial solar cells with different V_{OC}, but equal J_{SC} and fill factor. The cell with the highest V_{OC} (= 0.59 V) will be used as the bottom cell of a tandem structure. The other five cells have a V_{OC} of 0.54, 0.48, 0.41, 0.35 and 0.29 V, respectively, and will be used as top cell.

Table 1
Comparison between calculated and experimental parameters of the series and parallel tandem solar cell extracted from Fig. 5

Cell	J_{max} [A/m^2]	V_{max} [V]	J_{SC} [A/m^2]	V_{OC} [V]	FF [%]	η [%]
Calculated series	−5.64	0.91	−7.34	1.27	55	0.50
Experimental series	−6.00	0.89	−7.60	1.28	54	0.48
Calculated parallel	−66.3	0.39	−91.2	0.58	48	2.53
Experimental parallel	−64.8	0.40	−89.9	0.58	49	2.56

of tandem cells: we choose the characteristic of cell 1 ($V_{OC} = 0.59$ V) as bottom cell and then add all curves 2–6, subsequently as top cell. For each combination of 2 curves we then apply the method as explained above, and construct the resulting electrical tandem characteristics, when the cells are connected either in series or parallel. In this way, we can investigate the effect of a variation of the V_{OC} in one of the sub cells on the V_{OC} and performance of the tandem cells. In Fig. 7A the resulting V_{OC} of the tandem cell is plotted as a function of the V_{OC} of the top cell (ranging from 0.29 to 0.54 V). For the series connection it is evident that the V_{OC} of the tandem cell is equal to the sum of the open-circuit voltages of the different subcells. For the parallel connection the V_{OC} of the tandem cell (circles) is close, but not exactly equal to the V_{OC} of the top cell, which is the lowest of the two subcells (triangles). As shown in Fig. 3 the V_{OC} of the tandem cell is reached when the dark current of the cell with the lowest V_{OC} is cancelled by the photocurrent of the cell with the highest V_{OC}. Since, the increase of the dark current is very steep in that voltage region the V_{OC} of the tandem is slightly higher, but close to the open-circuit voltage of the cell with the lowest V_{OC}. As shown in Fig. 7B the efficiency of the series connection is considerably higher than the parallel connection. Since the J_{SC} is by definition matched and the voltages add up the efficiency of the series tandem cell is equal to the sum of the efficiencies of the subcells. Since, for the parallel connection the V_{OC} of the tandem is close to the lowest V_{OC} (Fig. 7A) the efficiency is limited by this cell. It should be noted that in these calculations we have assumed that stacking of both subcells does not change their absorption, as is the case for two subcells absorbing in a different region of the solar spectrum.

As a next step we consider the effect of a difference in the short-circuit current J_{SC} of the different subcells. In Fig. 8 a set of J–V characteristics is constructed in such a way that all cells have the same FF and V_{OC}, but a large variation in J_{SC} (from -88 A/m^2 to -26 A/m^2). Again, with these 6 cells as input we construct a series of tandem cells: we choose the characteristic of cell 1 ($J_{SC} = -88$ A/m^2) as bottom cell and then add all curves 2–6 ($J_{SC} = -61$ A/m^2 to -26 A/m^2) subsequently as top cell. In Fig. 9A the J_{SC} of the tandem cells are shown for the series and parallel connection as a function of the J_{SC} of the top cell. As expected, for the parallel connection of subcells with an equal V_{OC} the J_{SC} is equal to the sum of the J_{SC} of both subcells. For the series connection the J_{SC} of the tandem cell is slightly higher then the short-circuit current of the subcell with the lowest J_{SC} (top cell, triangles). As shown in Fig. 2 the J_{SC} of the tandem is at the point where the photocurrent in reverse bias (3rd quadrant) of the top cell is equal to the photocurrent in the top cell under forward bias (4th quadrant). Regarding the efficiency, shown in Fig. 9B, it is clear that for subcells with

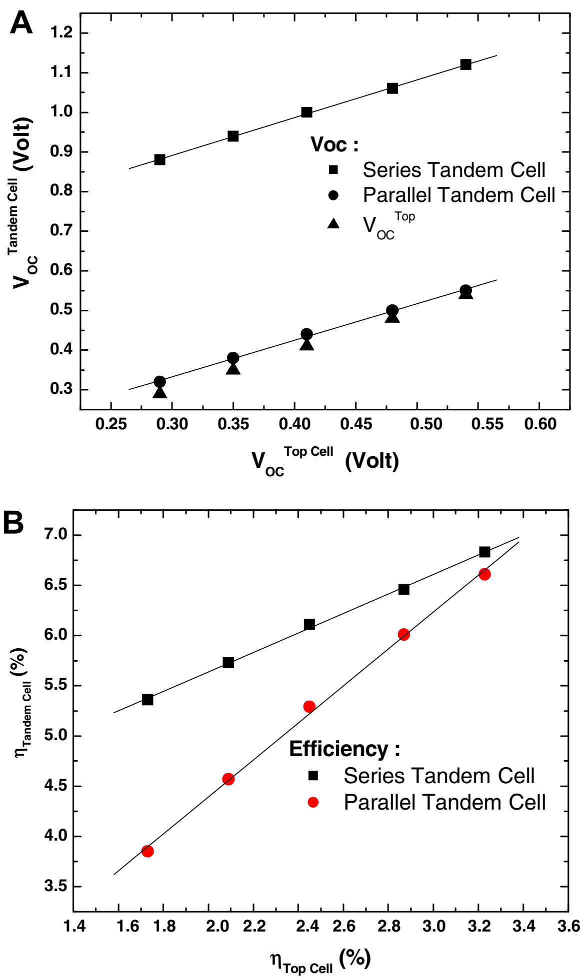

Fig. 7. (A) Open-circuit voltage of the tandem cell as a function of the V_{OC} of the top cells 1–5 from Fig. 6, both in series and parallel connection. Also shown is V_{OC} of the subcell with the lowest V_{OC} (top cell, triangles). (B) Efficiency of the series and parallel connection of the tandem cell as a function of the efficiency of the top cell. The efficiency of the parallel configuration is limited by the lower V_{OC} of the top cell.

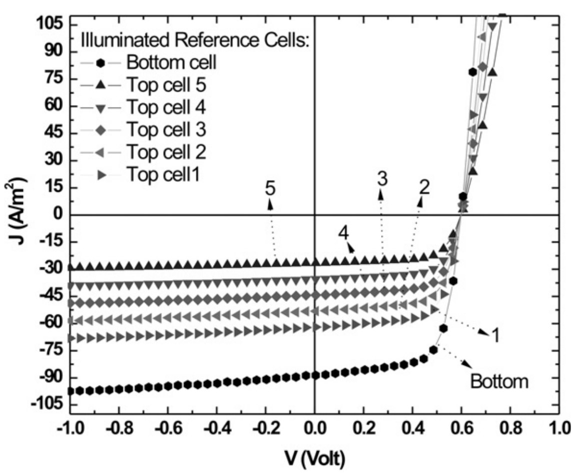

Fig. 8. Current–voltage characteristic of 6 artificial solar cells with different J_{SC}, but equal V_{OC} and fill factor. The cell with the highest J_{SC} (= 88 A/m^2) will be used as the bottom cell of a tandem structure. The other five cells have a J_{SC} of 62, 53, 44, 36 and 26 A/m^2, respectively, and will be used as top cell.

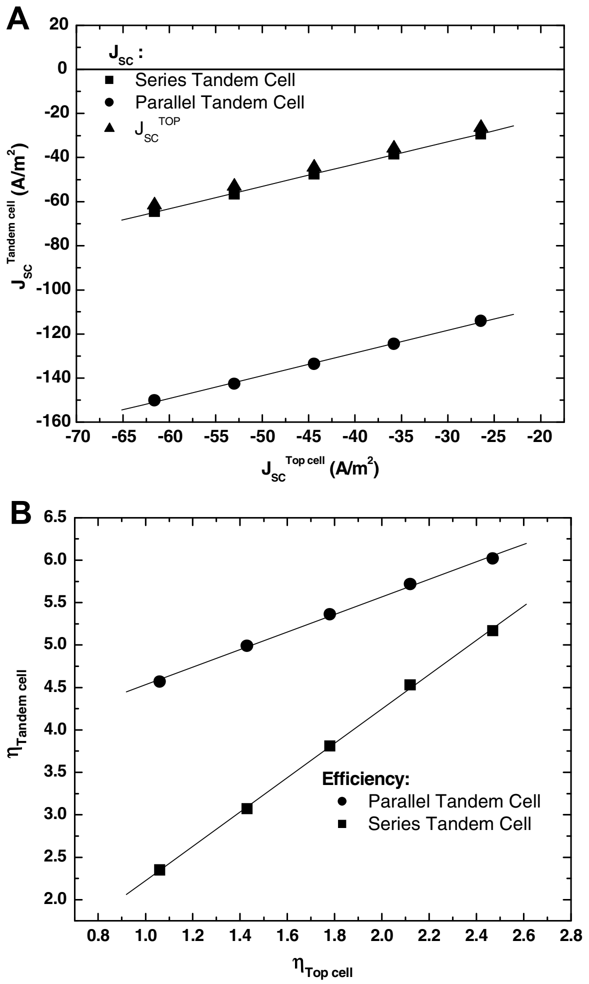

Fig. 9. (A) Short-circuit current of the tandem cell as a function of the J_{SC} of the top cells 1–5 from Fig. 8, both in series and parallel connection. Also shown is J_{SC} of the subcell with the lowest J_{SC} (top cell, triangles). (B) Efficiency of the series and parallel connection of the tandem cell as a function of the efficiency of the top cell. The efficiency of the series configuration is limited by the lower J_{SC} of the top cell.

equal V_{OC}, but varying J_{SC} the parallel connection is favorable, and the efficiency of the tandem cell is typically the sum of the efficiencies of the subcells. The efficiency of the series connection is limited (but not equal to) by the subcell with the lowest J_{SC}.

Another important question is how the fill factor of a tandem cell is affected, when one of the sub cells has a very poor FF. Will the FF of the tandem for example be closer to the highest or the lowest FF, when connected in series or parallel? To investigate this we consider a range of J–V characteristics as shown in Fig. 10. These artificial J–V curves are constructed in such a way that all cells have the same V_{OC} and J_{SC}, but a large variation in FF (from 25 to 66%). Each (artificial) solar cell has a different maximum power point (MMP), which results in a different maximum current (J_{max}) and maximum voltage (V_{max}) for each cell (Fig. 10).

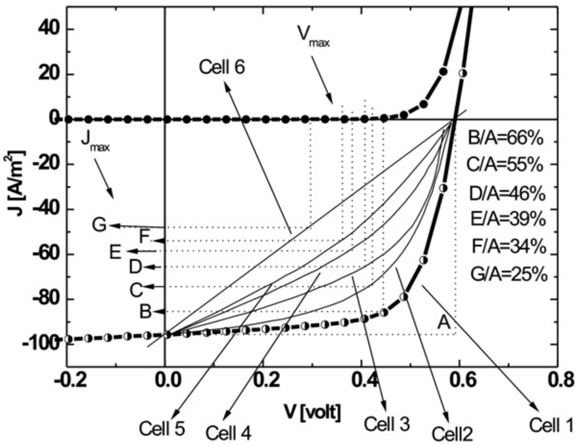

Fig. 10. Current–voltage characteristic of 6 artificial solar cells with different fill factors. The areas B/A = 0.66, C/A = 0.54, D/A = 0.44, E/A = 0.39, F/A = 0.31 and G/A = 0.25 demonstrates the fill factor of the cell 1 until the cell 6, respectively.

For the series connection the resulting J–V characteristics of the various tandem cells have the same short-circuit current ($J_{SC} = -95.3$ A/m^2) and open-circuit voltage ($V_{OC} = 1.18$ V), but different fill factors (FF) and efficiencies (η). For the parallel configuration the results of tandem cells based on the bottom cell (cell 1) with itself and the other 5 sub cells as top cells have the same short-circuit current ($J_{SC} = -190.6$ A/m^2) and open-circuit voltage ($V_{OC} = 0.59$ V) and also different fill factor (FF) and efficiencies (η). Fig. 11A demonstrates the different behavior of the series and parallel configuration tandem device when the fill factor of one sub cell is varied, in which the fill factor of the tandem devices is plotted as a function of the fill factor of the top cell. The mathematical average, which is the sum of the fill factors of the sub cells divided by two, is also plotted. When the two sub cells have an equal fill factors both the series and parallel configuration have that same fill factor. When the top cell has a significantly lower fill factor, the parallel configuration follows the mathematical average and shows a higher fill factor as compared to the series one. The lower fill factor of the top cell strongly decreases the fill factor of the series tandem device. Furthermore, the fill factors of the series tandem devices are higher than the fill factors of the top cells. Only when the bottom cell (cell 1) is combined in a tandem cell with itself, the fill factor of the tandem device equals to the fill factor of the bottom cell (cell 1, 66%). Combining the highest (66%) and lowest (25%) FF as sub cells in a series tandem device leads to a FF of 38%, which is below the average value (45.5%). The fill factor of the top cell limits the performance of the parallel tandem device as well by lowering its fill factor, equal to the series configuration. However, the fill factor of the parallel tandem cell is higher than the series configuration in all cases. The effect of the fill factors on the power conversion efficiency of the tandem cells is similar. The parallel tandem cell has higher efficiency than the series cell. The performances of all tandem cells considered are compared in Fig. 11B.

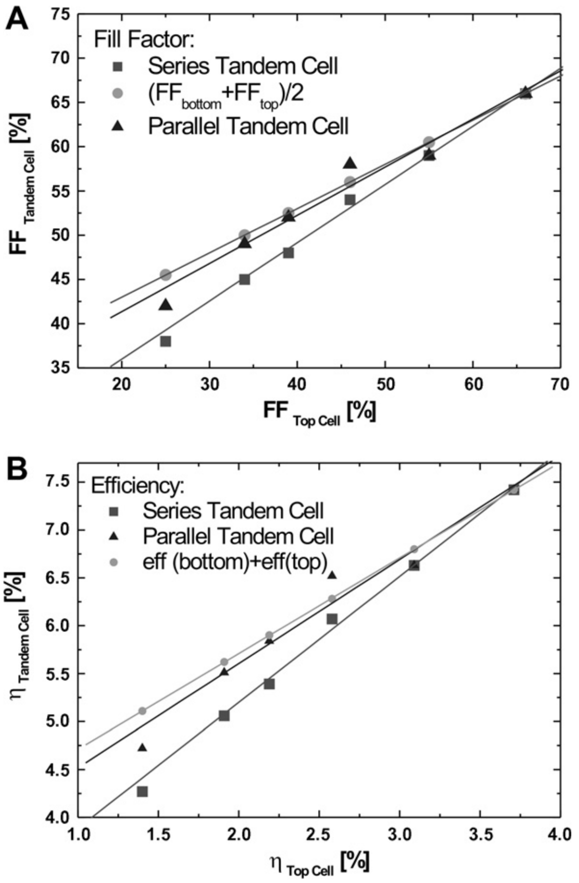

Fig. 11. (A) Fill factors of the tandem devices, series and parallel, as a function of the fill factor of the top cell and a bottom cell with a fill factor of 66%. The parallel configuration shows a higher fill factor as compared to the series configuration. (B) Efficiency of the series and parallel tandem cells considered as well as the sum of the efficiency of the sub cells as a function of the efficiency of the top cell. When both sub cells have similar electrical performance, both series and parallel configuration leads to nearly identical efficiencies. If one of the sub cells (top cell here) exhibits a lower fill factor, the parallel configuration is the better choice to fabricate.

5. Conclusions

A methodology is presented to derive the current–voltage characteristic of any arbitrary tandem device from the electrical performance of the individual sub cells. The calculated characteristics are in very good agreement with experimental data on both series and parallel connected tandem devices. In general, when both sub cells have almost the same electrical properties, series and parallel configurations lead to tandem devices with the same performance. If there are large differences in the open-circuit voltages, the series connection is a better geometry to choose since its overall efficiency is higher than the series configuration. On the other hand, for subcells with variations mainly in the short-circuit current the parallel connection is more advantageous. The mathematical average of the fill factors of the sub cells is a good approximation for the fill factor in the parallel configuration. The series configuration has significantly lower fill factor and therefore lower efficiency.

Acknowledgements

The authors gratefully acknowledge Jan Harkema and Frans van der Horst for their technical assistance, and Floris B. Kooistra and Prof. Jan C. Hummelen for providing PCBM.

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